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Journal

NeuroImage, 27(3)

ISSN

1053-8119

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Publication Date

2005-09-01

DOI

10.1016/j.neuroimage.2005.04.025

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Peer reviewed

Brain activation during execution and motor imagery of novel and skilled sequential hand movements

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Received 7 July 2004; revised 29 March 2005; accepted 4 April 2005

Available online 19 July 2005

This experiment used functional magnetic resonance imaging (fMRI) to compare functional neuroanatomy associated with executed and imagined hand movements in novel and skilled learning phases. We hypothesized that 1 week of intensive physical practice would strengthen the motor representation of a hand motor sequence and increase the similarity of functional neuroanatomy associated with executed and imagined hand movements. During fMRI scanning, a right-hand self-paced button press sequence was executed and imagined before (NOVEL) and after (SKILLED) 1 week of intensive physical practice ($n = 54$; right-hand dominant). The mean execution rate was significantly faster in the SKILLED (3.8 Hz) than the NOVEL condition (2.5 Hz) ($P < 0.001$), but there was no difference in execution errors. Activation foci associated with execution and imagery was congruent in both the NOVEL and SKILLED conditions, though activation features were more similar in the SKILLED versus NOVEL phase. In the NOVEL phase, activations were more extensive during execution than imagery in primary and secondary cortical motor volumes and the cerebellum, while during imagery activations were greater in the striatum. In the SKILLED phase, activation features within these same volumes became increasingly similar for execution and imagery, though imagery more heavily activated premotor areas, inferior parietal lobe, and medial temporal lobe, while execution more heavily activated the precentral/postcentral gyri, striatum, and cerebellum. This experiment demonstrated congruent activation of the cortical and subcortical motor system during both novel and skilled learning phases, supporting the effectiveness of motor imagery-based mental practice techniques for both the acquisition of new skills and the rehearsal of skilled movements.

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Keywords: Brain activation; Hand movement; Motor imagery

Introduction

Motor imagery is a mental event where the kinesthetic memory of a prior movement is reactivated, giving rise to an experience of re-executing the movement (Lacourse et al., in review). The functional neuroanatomy associated with movement execution and motor imagery (i.e., cognitive specific imagery; see Paivio, 1986) is partially congruent, with the magnitude and volume of brain activation more limited during imagery (Jeannerod, 1994). Experiments using positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) show regional activation during execution of novel movements in the supplementary motor area (SMA), primary motor cortex (M1), rolandic region, ventral premotor cortex (PMv), medial frontal cortex, cerebellum, and basal ganglia, while motor imagery of novel movements activates the SMA, M1, PMv, posterior parietal cortex, and cerebellum (Kim et al., 1995; Lafleur et al., 2002; Tyska et al., 1994), as well as descending motor pathways that facilitate spinal reflex excitability (Bonnet et al., 1997; Fadiga et al., 1999; Hale et al., 2003; Kiers et al., 1997; Yahagi et al., 1996). Evidence for congruent movement timing and motor control laws (Decety et al., 1989; Kohl and Fiecasaro, 1995; Papaxanthi et al., 2002) combined with similar autonomic response modulation (Jackson et al., 2001) further suggests that movement preparation and motor imagery are mediated by a common neural substrate (Jeannerod, 1994).

Congruent functional neuroanatomy associated with motor imagery and physical execution has prompted speculation that motor imagery practice paradigms might be efficacious for activating sensorimotor networks for the rehabilitation of movement disorders (Jackson et al., 2001; Johnson, 2000; Lacourse et al., 2004; Page et al., 2001; Robertson and Murre, 1999). For example, a stable motor representation mediating motor imagery might provide a substrate from which to re-establish functional motor circuits during neurorehabilitation or prevent maladaptive reorganization, particularly during the immobilization period when movements cannot be executed.

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Available online on ScienceDirect (www.sciencedirect.com).

Most studies showing congruent functional neuroanatomy during execution and motor imagery have used novel movement conditions (Hanakawa et al., 2003; Lotze et al., 1999; Porro et al., 1996), so it is unknown whether functional neuroanatomy is more or less congruent in a skilled (i.e., over-learned) movement condition. Jeannerod (1997) hypothesizes that a motor image is a conscious motor representation having the same properties as the corresponding overt movement. If true, it follows that the vividness or quality of a motor image would be related to the strength of the motor representation of the corresponding skill level of an individual.

Several studies report changes in functional neuroanatomy subsequent to physical practice, including M1 (Sanes, 2000), SMA (Jenkins et al., 1994; Toni et al., 1998), PMv (Jenkins et al., 1994; Jueptner et al., 1997a,b), posterior parietal cortex (Jenkins et al., 1994; Jueptner et al., 1997a,b), prefrontal cortex (Jenkins et al., 1994; Toni et al., 1998), cerebellum (Jenkins et al., 1994; Jueptner et al., 1997a,b; Toni et al., 1998), and striatum (Toni et al., 1998) that strengthen motor representations (Doyon and Ungerleider, 2002). In a novel learning phase where motor representations have yet to be encoded, a motor imagery episode might not fully activate the sensorimotor network associated with the corresponding overt movement. Greater congruence in functional neuroanatomy between physical execution and motor imagery would be expected for the skilled learning phase compared to the novel phase as an effect of a strengthened motor representation subsequent to practice.

Lafleur et al. (2002) used PET to compare functional neuroanatomy during physical execution and motor imagery of a foot movement in novel and skilled phases of learning. They report that parallel changes in sensorimotor activation associated with execution and imagery of foot movement did occur from novel to skilled phases, though it is unclear whether acquisition changed the degree to which brain activation during execution was congruent with activation during imagery. The goal of the present experiment was to use fMRI to compare functional neuroanatomy associated with executed and imagined hand movements in novel and skilled learning phases and to extend the findings of Lafleur et al. from the lower to the upper extremities. We hypothesized that 1 week of intensive physical practice would strengthen the motor representation of a hand motor sequence and increase the congruence in functional neuroanatomy between physical execution and motor imagery.

Methods

Participants

Fifty-four male ($n = 19$) and female ($n = 35$) right-hand dominant participants completed the experiment after providing informed consent. All were current university students, mean (SD) age = 24.5 (7.72) years. The Veterans Affairs Healthcare System, Long Beach Institutional Review Board (IRB) and the California State University, Long Beach IRB approved the protocol in accordance with the Helsinki Declaration of 1975, as revised in 1983. The mean (SD) handedness score, as determined with the Edinburgh Inventory (McFarland and Anderson, 1980), was 5.28 (3.16), indicating moderate to strong right-handedness. Exclusion criteria included history of seizures,

mental illness, substance abuse during the past 12 months, any major medical illness, alcoholism, or current use of a medication known to alter neurologic activity.

Motor task

A sequential button press task was performed using the right hand while it rested on a four-key response pad (Neuroscan, Inc.) during two test sessions and five physical practice sessions over 1 week. The button press sequence was 4–2–3–1–3–4–2, with the numbers (1–4) representing digits (index (1), middle (2), ring (3), and little finger (4)) (see Fig. 1). Participants attempted to perform the motor sequence during the two test sessions at a self-paced execution rate of 4 Hz.

Experimental design

All participants performed the motor task inside a magnetic resonance (MR) scanner during a pre-test session that followed a brief familiarization period. Two scanning sessions were completed during the pre-test—one where the participant physically pressed buttons on the response pad when the word “PUSH” was displayed and one where they imagined themselves pressing the buttons when “PUSH” was displayed. Half of the participants were randomized to perform the imagery scan session first, while the other half performed the button pressing session first. All participants then physically practiced the sequence for five consecutive business days. On the day following the fifth practice session, the participant returned to the MR scanner for a post-test session, which repeated the pre-testing and scanning. The resulting independent variables were learning phase (NOVEL (pre-test), SKILLED (post-test)) and test condition (Movement or Imagery scans), yielding four experimental conditions in a 2×2 repeated measures factorial design: NOVEL-Move; NOVEL-Image; SKILLED-Move; and SKILLED-Image. The dependent variables were brain activation and motor sequence performance. Brain activation was measured with blood oxygen level dependent (BOLD) fMRI. Motor sequence performance was evaluated by counting the number of completed sequences and errors during 30-s epochs of the Move task.

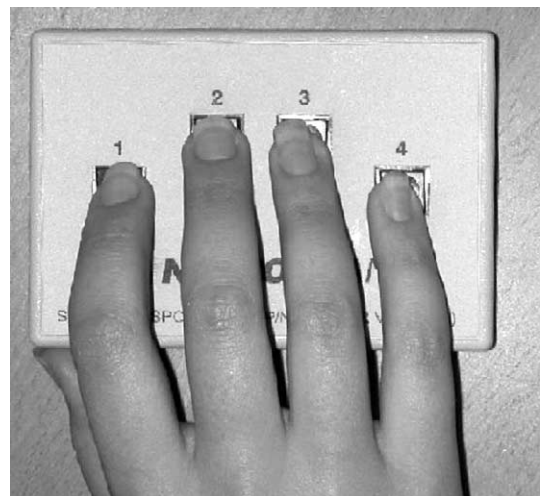


Fig. 1. Neuroscan button box used for hand motor sequence.

Test procedures

Participants were screened via telephone prior to the pre-test session. Upon arrival for the pre-test, the study was described, and the consent forms, Edinburgh Handedness Inventory, Movement Imagery Questionnaire (Hall and Martin, 1997) and Vividness of Movement Imagery Questionnaires (Isaac et al., 1986) were completed. Outside the MR scanner before the pre-test scan sessions, a standardized description of the motor task was provided and participants completed a task familiarization exercise, first by tapping their right index finger in time with a metronome (Qwik Time, QT-5) at 4 Hz to become familiar with the temporal requirement of the task. Next, they tapped a simple sequence (1–2–3–4, with fingers labeled as above) at 4 Hz for one 30-s epoch and then rehearsed the full test sequence (4–2–3–1–3–4–2) at 4 Hz (i.e., 4 button presses per second) for one 30-s epoch. Finally, participants completed one 30-s epoch of imagined sequence execution at 4 Hz. This standardized familiarization exercise was brief to preserve the novelty of the task inside the scanner but was deemed necessary from a pilot study that revealed confusion during scanning when participants were unfamiliar with the task. After completing the brief familiarization exercise, participants were prepared for testing inside the scanner and allowed one additional 30-s practice epoch to familiarize themselves with the “REST” and “PUSH” screens and with performing the task without seeing the button box. Participants were not provided any additional exposure to the sequence order or the pacing while inside the scanner; they therefore had to recall both. Two 3.5 min scan sessions, separated by a 5-min inter-session rest period, consisted of three 30-s epochs of Move or Image of the motor sequence using the following block paradigm: REST–PUSH–REST–PUSH–REST.

Practice procedures

After concluding the pre-test, participants were scheduled for practice sessions in the laboratory for each of the next five consecutive business days, consisting of repetitive cycles of rest (30 s) and practice (30 s) for 30 min each day. Participants were paced at 2 Hz during the first two practice sessions (slower than the mean execution rate of 2.5 Hz recorded during the pre-test session) so that the focus of learning was on establishing a representation of the sequence order. Pacing was increased to 4 Hz beginning the third practice session so that participants could then rehearse the temporal representation of the sequence. During each practice session, participants were paced for the first half (15 min) only. Performance was self-paced for the remaining 15 min. Participants were strongly encouraged to avoid practicing the sequence or even to think about the sequence outside of the laboratory sessions.

fMRI data acquisition methods

Magnetic resonance imaging was performed using a 1.5 T Eclipse scanner (Marconi Medical Systems, Inc., Cleveland, OH) equipped with multi-slice echo-planar imaging (EPI) capabilities and a receive-only head-coil. A high-resolution full-brain 3D anatomical image was acquired in the axial orientation for each participant at the beginning of the first session. The sequence used was a T1 relaxation-weighted 3D volume, RF spoiled fourier-acquired steady-state technique sequence (FAST) (TR (repetition time) = 22 ms, TE (echo time) = 7 ms, 25° flip angle, matrix =

256 × 256, in-plane resolution = 0.94 MM × 0.94 mm, slice thickness = 2.5 mm with no inter-slice gap).

The pulse sequence for the fMRI scans was a T2*-weighted gradient-echo echo-planar imaging sequence, with a TE of 40 ms, TR of 3.0 s, 90° flip angle, and a fat-saturating pre-pulse. Twenty eight axial slices covering the whole-brain were acquired in an interleaved order using a slice thickness of 5 mm with no inter-slice gap. The acquisition matrix was 64 × 64, which was interpolated to a final matrix size of 128 × 128. The field of view was 24 cm, leading to a resolution of 1.88 mm². A total of 70 frames were acquired during the two 3.5 min scan sessions (i.e., Move and Image). MRI-compatible silent vision™ goggles and silent scan™ headphones from Avotec (Jensen Beach, FL) were used for stimulus presentation and for communicating with participants. Inside the scanner, earplugs and headphones were fitted and head motion minimized by padding.

Data analysis

Motor behavior

Completed sequences, execution rate, and errors of omission (missing a button press) and commission (an incorrect button press) were recorded electronically for the three 30-s epochs of the Move task condition inside the MRI scanner during the pre- and post-tests. The mean execution rate and errors across the three epochs were computed for each test. Differences in motor sequence performance and number of errors between NOVEL and SKILLED conditions were analyzed using a paired *t* test.

fMRI

fMRI data analyses were performed by trained technicians, blind to subject identity and group membership. Image preprocessing and statistical analyses were performed on a sun firestorm workstation using SPM99 (Wellcome Department of Cognitive Neurology, Queen's College, London; <http://fil.ion.ucl.ac.uk/spm>) and MATLAB (Mathworks, Inc., Natick, MA). The first two images (i.e., 6 s) of each series were removed from further analysis to allow for tissue saturation. Remaining images were realigned to the first volume using a tri-linear interpolation algorithm, corrected for motion artifacts, co-registered to the participant's T1-weighted high-resolution anatomical scan, spatially normalized into standard stereotaxic space (EPI template provided by the Montreal Neurologic Institute, MNI), and spatially smoothed using a 4-mm full-width-at-half-maximum Gaussian kernel.

Within each participant, a fixed-effects analysis of the activation versus rest contrast during each of the four experimental conditions (i.e., NOVEL-Move (NM); NOVEL-Image (NI); SKILLED-Move (SM); SKILLED-Image (SI)) was performed using a single design matrix (modeled as four scan sessions). To test for condition effects at the first level, a general linear model was constructed (Doyon et al., 2003; Friston et al., 1995; Worsley and Friston, 1995) using a single boxcar regressor consisting of the alternating 30-s rest and Move or Image epochs. The boxcar waveform was convolved with the canonical hemodynamic response function and high pass filtered at 120 s (i.e., on–off cycle of 20 scans * 2 * 3 s/scan; see <http://fil.ion.ucl.ac.uk/spm>) to generate statistical contrast maps of interest. The contrasts of interest at the first level of analysis were the experimental condition effects (activation versus rest during NM, NI, SM, and SI), main effect of skill level ((NM + NI)–(SM + SI)), simple main effect of move versus image during novel learning condition

(NM–NI), simple main effect of move versus image during skilled learning condition (SM–SI), and the two way interaction of skill level and move/image state (NM–NI)–(SM–SI). The activation–rest contrast images based on the SPM {Z} statistics generated from each participant were then taken to a second-level random-effects analysis to test for group effects.

At the second level of analysis, the spatially normalized contrast maps from each participant were entered into a random-effects group analysis. A one-sample *t* test was performed across the individual SPM {Z} contrast images for each of the condition effects, main effects, simple main effects, and interaction effects to test the null hypotheses that the mean activation in each anatomical volume of interest is zero. Statistical significance for the computed SPM {t} statistics was established at a height threshold of 6.50 ($P < 0.001$; whole brain corrected) and a spatial extent threshold of 10 contiguous voxels. The three measures of activation for each volume of interest were the location of local maxima (i.e., *x*, *y*, *z* coordinates; MNI-space), magnitude (i.e., *t* statistic for local maxima), and extent (i.e., number of activated voxels in a cluster).

To identify significantly activated clusters within our anatomical volumes of interest (VOI), we used the Anatomical Automatic Labeling method that is based on the spatially normalized single-subject high resolution T1 volume provided by the MNI (Tzourio-Mazoyer et al., 2002). The anatomical VOI were established as those brain areas previously found to be activated during either execution or motor imagery of a novel hand motor sequence. A summary of studies identifying those activated volumes is available in Lafleur et al. (2002) and includes the precentral gyrus (primary motor cortex; M1), postcentral gyrus (primary somatosensory cortex; S1), supplementary motor area (SMA), superior frontal gyrus (ventral premotor cortex; PMv), cerebellum, thalamus, striatum (caudate nucleus and putamen), cingulate, inferior posterior parietal lobe (IPL), and superior posterior parietal lobe (SPL). There is recent evidence for activation of medial and superior temporal lobes during motor imagery (Lacourse et al., in review), so these newly identified regions were also examined.

Results

Motor imagery questionnaires

The mean (SD) of scores on the Movement Imagery Questionnaire (maximum score = 28) and Vividness of Movement

Imagery Questionnaire (maximum score = 120) were 22.6 (4.9) and 94.3 (24.2) respectively. Both scores indicate that participants possessed moderate to good motor imagery ability. There were no significant correlations between the tests of imagery ability and gains in motor execution rate or with motor sequence performance in the NOVEL and SKILLED conditions ($P > 0.05$), indicating that motor sequence performance and learning were independent of motor imagery ability.

Within-session motor performance

The mean (SD) execution rate for the three epochs during the pre- and post-test sessions is presented in Fig. 2. There were no significant differences in the mean execution rate between the three epochs within either test session ($P > 0.05$), and the inter-epoch correlations (*r*) ranged from .75–.90 for the pre-test and .90–.95 for the post-test, indicating that execution rate was constant across epochs and that participants were consistent during the fMRI data collection sessions.

Between-session motor performance

The mean (SD) execution rate and errors of omission and commission for the NOVEL-Move and SKILLED-Move conditions are presented in Fig. 3. The mean execution rate was significantly faster in the SKILLED than the NOVEL condition ($t(53) = 14.75$; $P < 0.001$), however, there was no significant difference in the number of errors between NOVEL and SKILLED ($t(53) = 0.67$; $P > 0.05$). The correlation in execution rate between NOVEL-Move and SKILLED-Move was .60, indicating that performance gains from the NOVEL to SKILLED phases were moderately consistent across participants.

Brain activation in the NOVEL condition

Table 1 summarizes the results from the one-sample *t* test for each of the four experimental conditions, Fig. 4 presents the image maps for each condition, and Fig. 5 presents effect sizes. During NOVEL-Move, activation was extensive in contralateral M1, S1, and PMv as well as in the SMA extending bilaterally. There was additional activation in homologous anatomical volumes within the ipsilateral hemisphere, although less extensive. Activation of the cerebellum was extensive in the bilateral hemispheres and vermis, while activation of only a small number of voxels was observed in the striatum (putamen and caudate nucleus). Additional activated

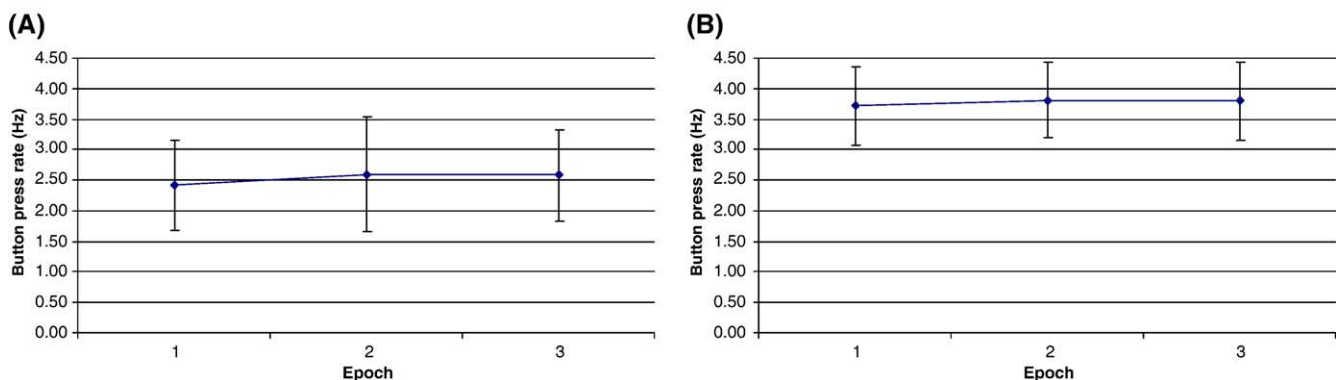


Fig. 2. Mean (SD) button press rate for the three 30-s epochs of movement execution within the pre-test (A) and post-test (B) sessions.

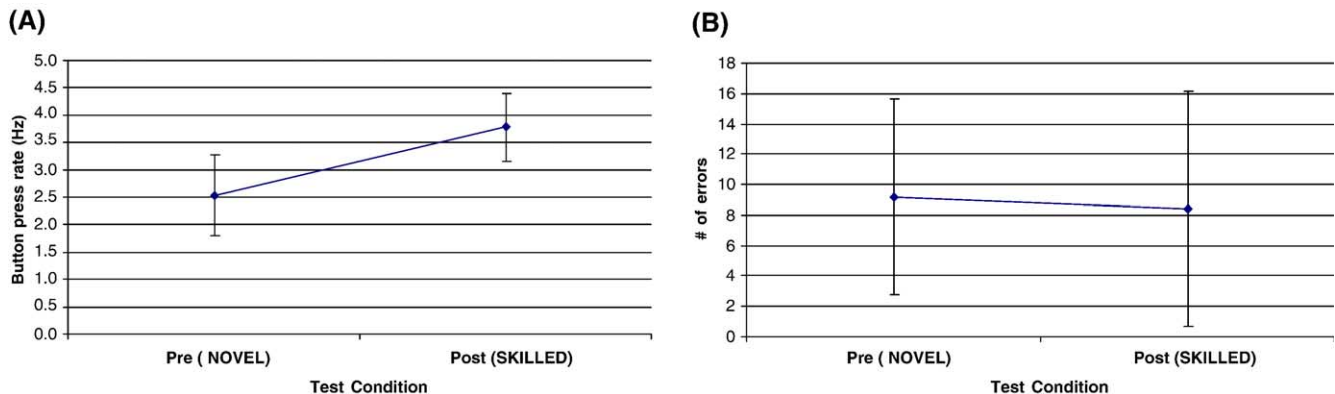


Fig. 3. Mean (SD) button press rate (A) and number of errors (B) for the pre-test and post-test conditions.

areas include SPL and IPL, bilateral thalamus, and cingulate gyrus (anterior and middle).

Clusters in the same anatomical areas were activated during NOVEL-Image, although the ratio of activated voxels during Image versus Move across all VOI was only .36. For a specific subset of cortical sensorimotor volumes (SMA + PMv + M1 + S1), the Image/Move ratio of activated voxels was .37. The greatest differences between the Image and Move conditions were in the SPL and IPL, where the Image/Move ratio of activated voxels was .26.

Brain activation in the SKILLED condition

Activation during SKILLED-Move was again extensive in contralateral M1, S1, and PMv as well as SMA, although the total number of significantly activated voxels across all anatomical VOI decreased by 35%, from 10,185 in NOVEL-Move to 6653 in SKILLED-Move (see Table 1 and Figs. 4, 5). The ipsilateral hemisphere was again activated in homologous anatomical volumes, though much less extensively than in the contralateral hemisphere.

Activation of the cerebellum was relatively unchanged from NOVEL-Move, while activation of the striatum increased substantially. In contrast to the NOVEL condition, there were no significant clusters in the SPL, while the IPL was activated less extensively than in the NOVEL-Move condition. Both the thalamus and cingulate were again activated, though less extensively than in the NOVEL condition.

Clusters in the same anatomical areas were activated during SKILLED-Image, with signal intensity of the local maxima in the clusters approximately equal to SKILLED-Move. The Image/Move ratio of activated voxels increased from the .36 found in the NOVEL condition to .61 in the skilled condition, reflecting both increased extent of activation associated with SKILLED-Image and decreased extent of activation associated with SKILLED-Move. The Image/Move ratio of activated voxels increased to .84 in the cortical sensorimotor volumes (i.e., SMA + PMv + M1 + S1) and to 1.62 in the SPL and IPL volumes.

Differences between Move and Image in the NOVEL condition

The primary question in this experiment was whether brain activation associated with physical execution and motor imagery is more or less congruent in novel versus skilled motor learning phases. To answer this question, statistical contrasts were per-

formed between Move and Image conditions in the NOVEL and SKILLED phases (see Table 2 and Fig. 6 for results). For the NOVEL phase, activation was significantly greater during NOVEL-Move than NOVEL-Image in frontal lobe clusters, including bilateral SMA extending inferior into the cingulate gyrus as well as the contralateral precentral gyrus (M1) extending anterior into ventral premotor areas. Activation was also greater in bilateral postcentral and supramarginal gyri and superior temporal lobe. Subcortically, activation was greater during Move in the ipsilateral cerebellar hemisphere and vermis as well as bilateral thalamus. Activation was significantly greater during NOVEL-Image than NOVEL-Move only in the bilateral caudate nucleus.

Differences between Move and Image in the SKILLED condition

Statistical contrasts were also performed between the Move and Image conditions in the SKILLED learning phase (see Table 3 and Fig. 7 for results). Activation was significantly greater during Move versus Image in clusters located within the contralateral precentral and postcentral gyri as well as SMA extending inferior into the cingulate gyrus. There was also more extensive activation during the Move conditions in the SPL, extending into the superior temporal lobe, rolandic area, insula, and supramarginal gyrus. Subcortically, activation was greater in the ipsilateral cerebellar hemisphere and vermis as well as contralateral thalamus. In contrast, activation was significantly greater during Image versus Move conditions in contralateral premotor areas, including medial superior and inferior frontal areas, as well as contralateral supramarginal gyrus, IPL, and medial temporal lobe.

Striatal versus cerebellar activation

The dynamic interaction of cerebellar and striatal circuits during motor learning is of great interest (Doyon et al., 2003). To investigate the interaction of cerebellar and striatal circuits during motor learning, we compared the extent of activation in these regions across the NOVEL and SKILLED learning phases. For the Move condition, the number of significantly activated voxels in the striatum increased from six during the NOVEL phase to 730 during the SKILLED phase, while the number of voxels in the cerebellar hemispheres and vermis increased only slightly from 1667 to 1710. A Chi-square test showed that these comparative gains in the number of activated

Table 1

Comparison of activated voxels, t statistics, and local maxima in anatomical regions of interest during the NOVEL and SKILLED learning phases for Move and Image task conditions (height threshold = $P < 0.05$; whole brain corrected; extent threshold = 5 voxels)

| Brain region | Hemisphere | BA | NOVEL | | | | | | | | | | SKILLED | | | | | | | | | |
|----------------------|---------------|----|-------------|--------------|-----|-----|----------------------|-------------|--------------|-----|-----|----------------------|-------------|--------------|-----|-----|----------------------|-------------|--------------|-----|-----|----------------------|
| | | | Move | | | | | Image | | | | | Move | | | | | Image | | | | |
| | | | # of voxels | Local maxima | | | $\{t\}$ $df = 53$ | # of voxels | Local maxima | | | $\{t\}$ $df = 53$ | # of voxels | Local maxima | | | $\{t\}$ $df = 53$ | # of voxels | Local maxima | | | $\{t\}$ $df = 53$ |
| | | | | x | y | z | | | x | y | z | | | x | y | z | | | x | y | z | |
| <i>Frontal lobe</i> | | | | | | | | | | | | | | | | | | | | | | |
| Sup. frontal gyrus | Contralateral | 6 | 417 | −26 | −4 | 58 | 12.35 | 335 | −22 | −4 | 58 | 11.86 | 126 | −56 | 8 | 22 | 7.99 | 397 | −46 | 12 | 6 | 8.03 |
| Precentral gyrus | Contralateral | 4 | 1182 | −32 | −18 | 48 | 10.77 | 375 | −36 | −20 | 52 | 7.81 | 726 | −26 | −12 | 52 | 12.56 | 682 | −36 | −20 | 52 | 7.27 |
| Sup. frontal gyrus | Ipsilateral | 6 | 237 | 40 | 32 | 26 | 8.68 | 15 | 34 | 24 | −2 | 6.73 | 28 | 54 | 10 | 12 | 9.27 | 55 | 38 | 36 | 20 | 8.02 |
| Precentral gyrus | Ipsilateral | 4 | 431 | 34 | −18 | 54 | 9.63 | 55 | 28 | −8 | 52 | 9.31 | 31 | 28 | −10 | 54 | 8.83 | 26 | 32 | −14 | 50 | 7.80 |
| SMA | Bilateral | 6 | 1248 | 6 | 2 | 56 | 11.78 | 735 | 4 | 0 | 58 | 11.14 | 813 | 2 | −2 | 62 | 10.45 | 895 | 0 | 2 | 58 | 14.22 |
| Cingulate | Bilateral | | 327 | −6 | −6 | 52 | 9.87 | 283 | 2 | −8 | 50 | 6.74 | 159 | −10 | −26 | 44 | 8.27 | 134 | 8 | 18 | 40 | 7.99 |
| <i>Parietal lobe</i> | | | | | | | | | | | | | | | | | | | | | | |
| Postcentral gyrus | Contralateral | 2 | 1458 | −42 | −32 | 44 | 15.00 | 394 | −50 | −24 | 32 | 12.40 | 1160 | −38 | −28 | 46 | 13.67 | 364 | −52 | −4 | 40 | 8.85 |
| Sup. parietal lobe | Contralateral | 7 | 316 | −24 | −56 | 58 | 12.56 | | | | | | | | | | | 65 | −18 | −66 | 54 | 8.63 |
| Inf. parietal lobe | Contralateral | 40 | 1024 | −36 | −40 | 50 | 14.24 | 482 | −42 | −30 | 42 | 13.60 | 467 | −32 | −48 | 52 | 8.45 | 833 | −42 | −46 | 48 | 9.17 |
| Postcentral gyrus | Ipsilateral | 2 | 162 | 48 | −34 | 44 | 12.31 | | | | | | | | | | | | | | | |
| Sup. parietal lobe | Ipsilateral | 7 | 178 | 20 | −58 | 58 | 7.47 | | | | | | | | | | | | | | | |
| Inf. parietal lobe | Ipsilateral | 40 | 519 | 40 | −44 | 52 | 12.78 | 56 | 34 | −50 | 42 | 6.85 | 84 | 38 | −54 | 48 | 8.69 | 59 | 48 | −38 | 40 | 8.16 |
| <i>Subcortical</i> | | | | | | | | | | | | | | | | | | | | | | |
| Cerebellum | Contralateral | | 499 | −22 | −56 | −28 | 9.88 | 29 | −6 | −50 | −18 | 7.30 | 467 | −20 | −56 | −24 | 9.59 | 21 | −34 | −52 | −32 | 8.14 |
| Cerebellum | Ipsilateral | | 592 | 20 | −56 | −28 | 13.89 | 155 | 18 | −56 | −22 | 8.60 | 607 | 20 | −56 | −26 | 13.15 | 76 | 24 | −64 | −24 | 7.72 |
| Vermis | Bilateral | | 576 | 4 | −62 | −20 | 13.77 | 197 | 2 | −62 | −18 | 8.52 | 636 | 4 | −62 | −16 | 14.66 | 8 | −2 | −50 | −10 | 6.94 |
| Caudate | Ipsilateral | | | | | | | 20 | 20 | 0 | 14 | 8.55 | 17 | 22 | −8 | 22 | 9.61 | 5 | 20 | −4 | 16 | 8.12 |
| Putamen | Contralateral | | 6 | −32 | −20 | −6 | 7.29 | 197 | −24 | −4 | 12 | 10.15 | 575 | −28 | −2 | −8 | 11.21 | 327 | −28 | −14 | −2 | 8.79 |
| Putamen | Ipsilateral | | | | | | | | | | | | 138 | 30 | −4 | 8 | 8.79 | | | | | |
| Thalamus | Contralateral | | 596 | −14 | −20 | 8 | 12.49 | 359 | −14 | −20 | 8 | 10.35 | 538 | −16 | −22 | 6 | 14.58 | 100 | −16 | −10 | 8 | 8.87 |
| Thalamus | Ipsilateral | | 365 | 10 | −16 | −8 | 9.64 | 35 | 14 | −20 | 8 | 7.17 | 81 | 18 | −14 | 10 | 8.99 | | | | | |

Note. MNI coordinates; Labels: SMA—supplementary motor area; Sup.—superior; Inf.—inferior; BA—Brodmann's area.

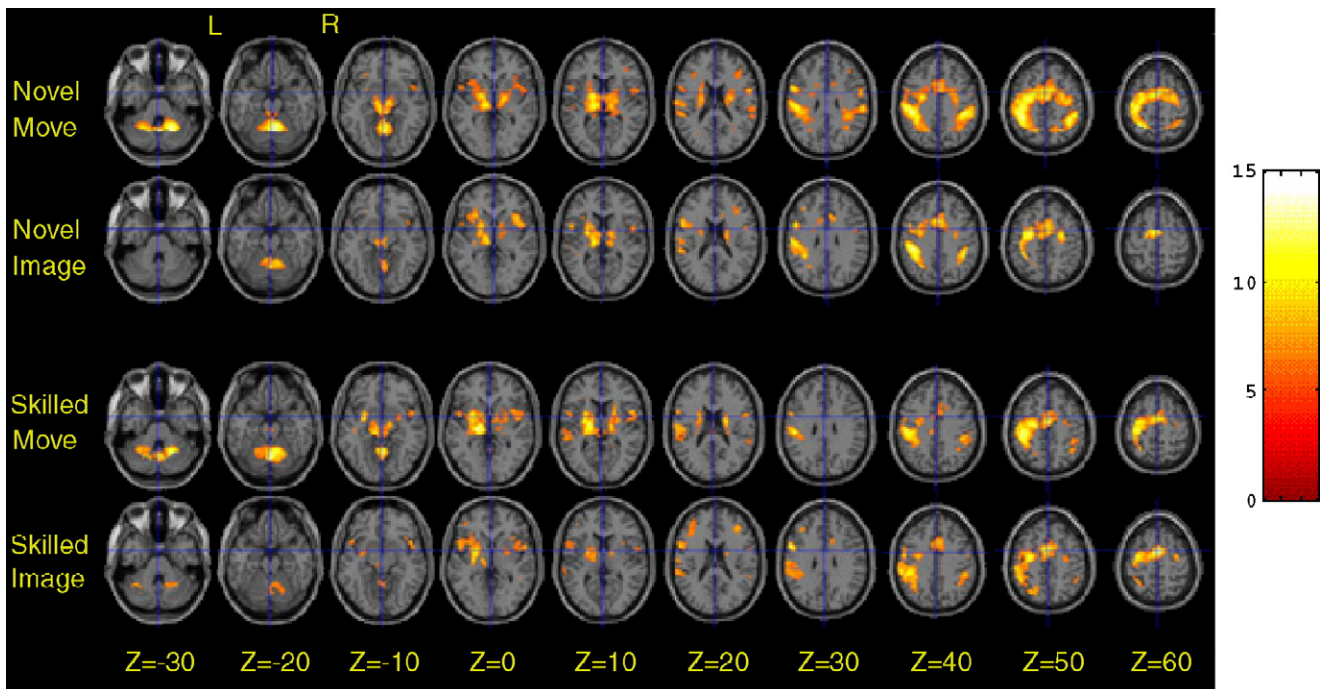


Fig. 4. Statistically significant activation maps using one-sample t test ($n = 54$), shown by condition and incremental z levels. The cluster threshold was set at $P < 0.001$, whole brain corrected with an extent threshold of 5 voxels and a threshold t statistic of 6.5. Crosshairs are centered at (0,0). Image shown per neurological convention: L, left hemisphere; R, right hemisphere.

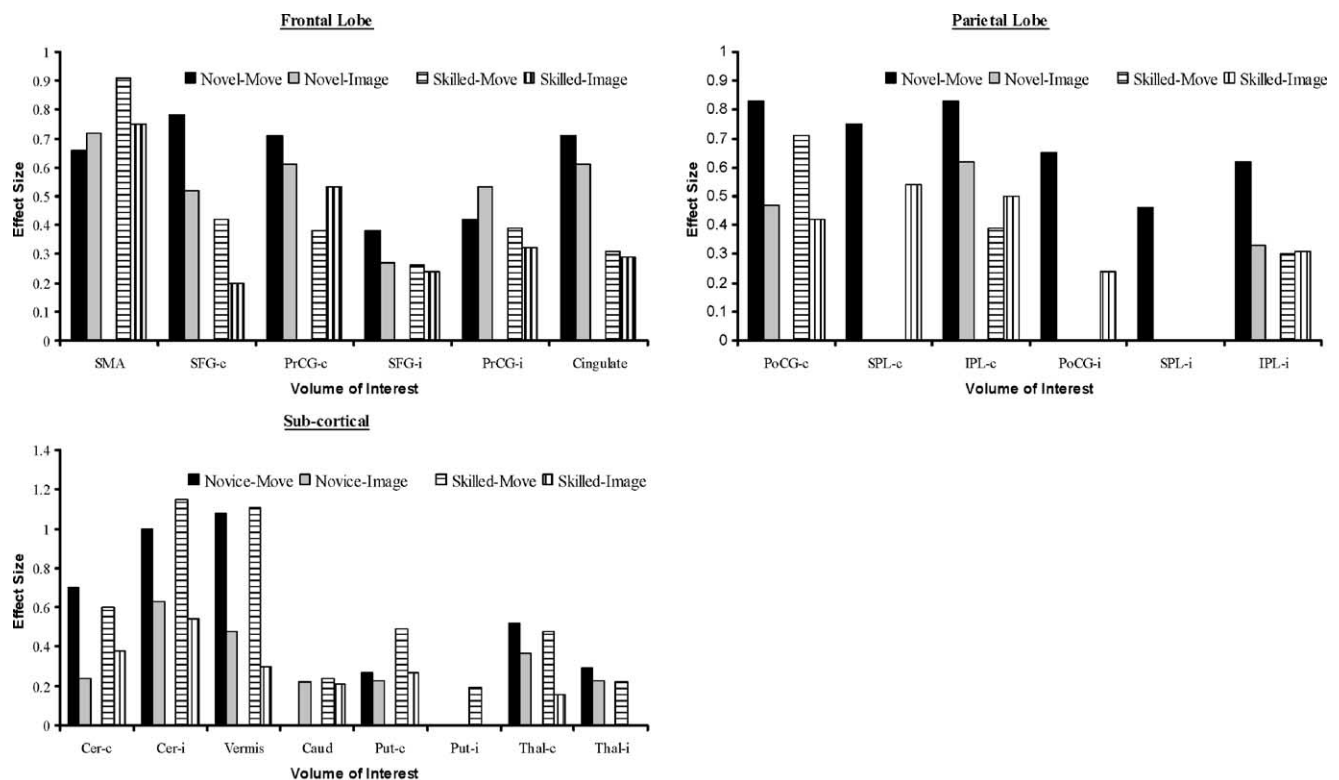


Fig. 5. Effect size of the local maxima within volumes of interest during NOVICE and SKILLED execution and motor imagery. Abbreviations: supplementary motor area—SMA; contralateral superior frontal gyrus—SFG-c; ipsilateral superior frontal gyrus—SFG-i; contralateral precentral gyrus—PrCG-c; ipsilateral precentral gyrus—PrCG-i; cingulate—Cing; contralateral postcentral gyrus—PoCG-c; ipsilateral postcentral gyrus—PoCG-i; contralateral superior parietal lobe—SPL-c; ipsilateral superior parietal lobe—SPL-i; contralateral inferior parietal lobe—IPL-c; ipsilateral inferior parietal lobe—IPL-i; contralateral cerebellum—Cer-c; ipsilateral cerebellum—Cer-i; caudate—caud; contralateral putamen—Put-c; ipsilateral putamen—Put-i; contralateral thalamus—Thal-c; ipsilateral thalamus—Thal-i.

Table 2

Brain areas where activation was significantly different between image and execution in the novel condition

| Contrast | Lobe | Anatomical region | Side | Local maxima coordinates (x, y, z) | | | Cluster size (voxels) | t | z |
|------------------------|-------------|---------------------------------------|------|------------------------------------|-----|-----|-----------------------|------|------|
| <i>Image > Move</i> | | | | | | | | | |
| | Subcortical | | | | | | | | |
| | | Caudate nucleus | L | −10 | 18 | 4 | 16 | 3.60 | 3.39 |
| | | Caudate nucleus | R | 18 | 18 | 4 | 8 | 3.84 | 3.59 |
| <i>Move > Image</i> | | | | | | | | | |
| | Frontal | | | | | | | | |
| | | Inferior frontal operculum/insula | L | −38 | 12 | 12 | 19 | 5.14 | 4.61 |
| | | Precentral/postcentral gyrus | L | −34 | −24 | 54 | 456 | 8.06 | 6.49 |
| | | SMA/anterior cingulate gyrus | L | −4 | −18 | 46 | 27 | 4.20 | 3.88 |
| | | SMA | L | −10 | −14 | 58 | 12 | 3.65 | 3.43 |
| | | SMA/anterior cingulate gyrus | R | 6 | 0 | 44 | 20 | 3.83 | 3.58 |
| | | SMA/anterior cingulate gyrus | R | 6 | −8 | 50 | 16 | 3.84 | 3.59 |
| | | SMA | R | 10 | −10 | 58 | 13 | 4.03 | 3.75 |
| | Parietal | | | | | | | | |
| | | Postcentral gyrus/inferior parietal | L | −32 | −38 | 48 | 39 | 4.02 | 3.74 |
| | | Postcentral gyrus/supramarginal gyrus | L | −50 | −26 | 30 | 93 | 5.11 | 4.58 |
| | | Postcentral gyrus/supramarginal gyrus | R | 50 | −26 | 32 | 27 | 4.67 | 4.25 |
| | | Postcentral gyrus | R | 30 | −26 | 44 | 14 | 4.61 | 4.21 |
| | Temporal | | | | | | | | |
| | | Superior temporal/rolandic operculum | L | −48 | −22 | 12 | 23 | 4.22 | 3.90 |
| | Subcortical | | | | | | | | |
| | | Cerebellar vermis/hemispheres | R | 6 | −62 | −20 | 586 | 6.43 | 5.50 |
| | | Thalamus | L | −16 | −22 | 2 | 320 | 4.87 | 4.41 |
| | | Thalamus | R | 10 | −16 | −10 | 26 | 4.03 | 3.74 |

voxels from NOVEL to SKILLED phases were significantly different between the striatum and cerebellum ($\chi^2(1) = 590.23$; $P < 0.001$).

For the Image condition, the number of significantly activated voxels in the striatum increased from 217 during the NOVEL phase to 332 during the SKILLED phase, while the number of significant voxels in the cerebellar hemispheres and vermis decreased from 381 to 105. Again, the comparative change in number of activated voxels from the NOVEL to SKILLED phases was significantly different between the striatum and cerebellum ($\chi^2(1) = 159.64$; $P < 0.001$).

Differences between NOVEL and SKILLED conditions

Statistical contrasts were performed between NOVEL-Move and SKILLED-Move and between NOVEL-Image and SKILLED-Image to examine physical practice-related effects on brain activation associated with movement and imagery (see Table 4 for results). Activation was significantly greater during NOVEL-Move versus SKILLED-Move in several clusters located within the anatomical VOI, particularly in the frontal lobe, and included clusters in the superior and inferior frontal lobe, SMA, and precentral gyrus. Additional

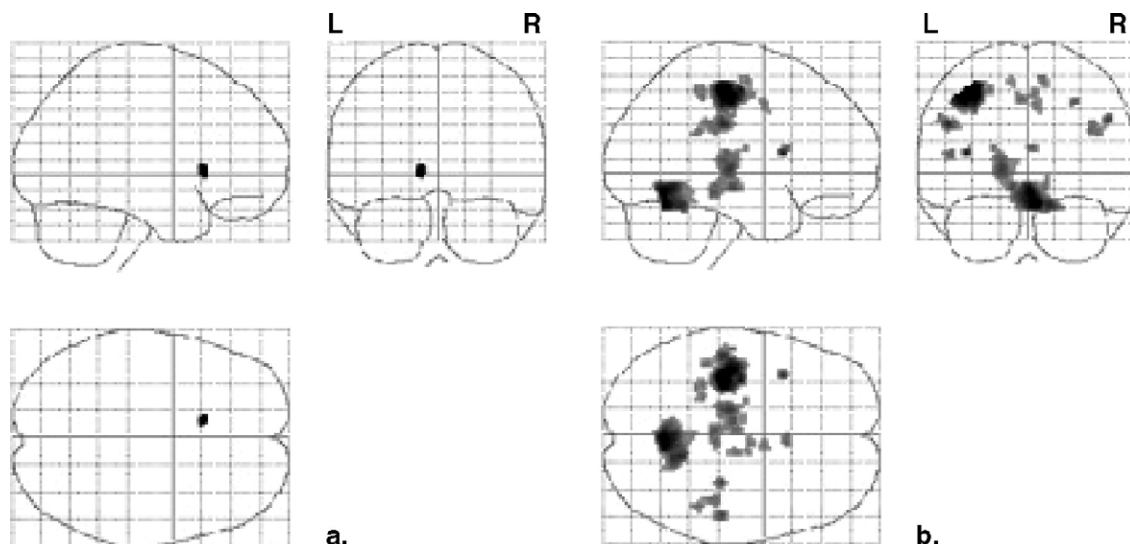


Fig. 6. The glass brain projections represent the statistical parametric map ($P < 0.001$ uncorrected) of regions showing greater activation during imagery versus execution (a) and execution greater than imagery (b) in the novel condition (height threshold = 3.25, extent threshold = 10 voxels, $df = 53$).

Table 3

Brain areas where activation was significantly different between Image and Move in the skilled condition

| Lobe | Anatomical region | 2 | Local maxima coordinates (x, y, z) | | | Cluster size (voxels) | t | z |
|------------------------|--|---|------------------------------------|-----|-----|-----------------------|------|------|
| <i>Image > Move</i> | | | | | | | | |
| Frontal | | | | | | | | |
| | Medial superior frontal | L | −20 | 18 | 48 | 30 | 4.73 | 4.30 |
| | Inferior frontal gyrus | L | −52 | 22 | 22 | 106 | 4.69 | 4.27 |
| | Middle frontal gyrus/precentral gyrus | L | −36 | 16 | 42 | 26 | 4.55 | 4.16 |
| Parietal | | | | | | | | |
| | Supramarginal gyrus/inferior parietal | L | −50 | −40 | 32 | 10 | 3.79 | 3.55 |
| Temporal | | | | | | | | |
| | Middle temporal/supramarginal/angular gyrus | L | −48 | −56 | 18 | 31 | 4.00 | 3.76 |
| <i>Move > Image</i> | | | | | | | | |
| Frontal | | | | | | | | |
| | Postcentral/precentral gyri | L | −32 | −24 | 56 | 597 | 8.16 | 6.54 |
| | Middle cingulate/SMA | L | −6 | −8 | 48 | 16 | 3.74 | 3.51 |
| | Middle cingulate/SMA | L | −8 | −26 | 46 | 43 | 3.98 | 3.70 |
| Parietal | | | | | | | | |
| | Postcentral/superior temporal gyrus/rolandic operculum | L | −46 | −28 | 26 | 341 | 5.48 | 4.85 |
| | Cuneus | L | −12 | −60 | 22 | 10 | 3.74 | 3.51 |
| Temporal | | | | | | | | |
| | Rolandic operculum/insula | L | −42 | 0 | 14 | 56 | 5.11 | 4.59 |
| | Rolandic operculum/superior temporal | R | 52 | −24 | 18 | 41 | 4.35 | 4.00 |
| | Superior temporal gyrus | R | 44 | −14 | 0 | 74 | 4.91 | 4.44 |
| | Superior temporal gyrus | L | −44 | −12 | 2 | 86 | 4.81 | 4.36 |
| | Superior temporal/supramarginal gyri | R | 54 | −36 | 22 | 14 | 4.18 | 3.87 |
| | Posterior cingulate gyrus | R | 12 | −36 | 14 | 11 | 3.99 | 3.72 |
| Subcortical | | | | | | | | |
| | Thalamus | L | −16 | −22 | 4 | 363 | 5.94 | 5.18 |
| | Cerebellar vermis/hemispheres | R | 2 | −62 | −16 | 1178 | 9.31 | 7.14 |

VOI where activation decreased in the SKILLED condition included clusters located in the bilateral IPL and thalamus as well as contralateral medial and inferior temporal lobe. There were no clusters located within anatomical VOI where activation was significantly greater in the SKILLED versus NOVEL conditions.

Activation was significantly greater for the NOVEL-Image than SKILLED-Image in frontal premotor and motor regions bilaterally,

as well as bilateral IPL and ipsilateral temporal lobe, while there were no clusters within VOI where activation increased.

Discussion

fMRI was used to determine whether the congruent brain activations associated with physical execution and motor imagery

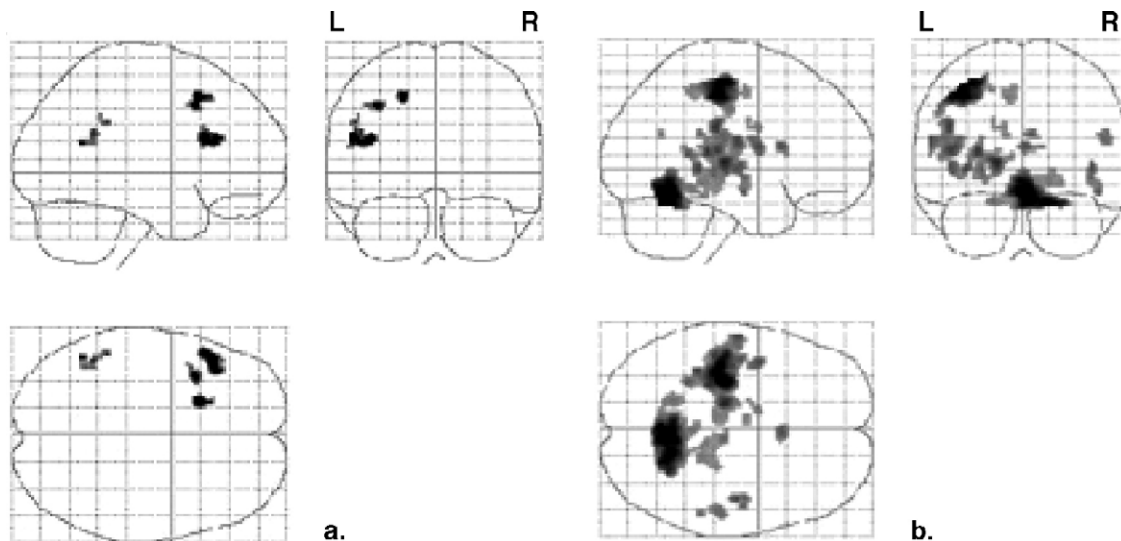


Fig. 7. The glass brain projections represent the statistical parametric map ($P < 0.001$ uncorrected) of regions showing greater activation during imagery versus execution (a) and execution greater than imagery (b) in the skilled condition (height threshold = 3.25, extent threshold = 10 voxels, $df = 53$).

Table 4

Brain areas where activation was different between novel and skilled conditions for execution and imagery

| Anatomical region | | Local maxima coordinates (x, y, z) | | | | Cluster size (voxels) | t | z |
|----------------------------------|--|------------------------------------|-----|-----|----|-----------------------|------|------|
| <i>Novel > Skilled, Move</i> | | | | | | | | |
| Frontal | | | | | | | | |
| | Precentral/superior–medial–frontal | L | –26 | 4 | 50 | 506 | 5.91 | 5.16 |
| | Precentral | L | –42 | 8 | 42 | 16 | 4.14 | 3.83 |
| | SMA/anterior cingulate gyrus | L | –2 | 12 | 50 | 169 | 4.35 | 4.00 |
| | Inferior–frontal | L | –40 | 32 | 22 | 126 | 5.11 | 4.59 |
| | Inferior–frontal/insula | L | –32 | 30 | –8 | 24 | 4.34 | 4.00 |
| | Precentral/postcentral gyri | R | 32 | –12 | 42 | 312 | 5.57 | 4.92 |
| | Precentral gyrus/inferior frontal | R | 46 | 8 | 30 | 16 | 4.28 | 3.94 |
| | Inferior–middle–frontal | R | 32 | 36 | 12 | 126 | 5.41 | 4.81 |
| | Inferior–frontal/insula | R | 46 | 24 | –6 | 13 | 4.01 | 3.73 |
| Parietal | | | | | | | | |
| | Inferior parietal | L | –44 | –34 | 32 | 942 | 6.21 | 5.36 |
| | Pre-cuneus | R | 10 | –60 | 50 | 33 | 5.00 | 4.50 |
| | Middle cingulate gyrus | R | 18 | –32 | 34 | 16 | 3.97 | 3.70 |
| | Supramarginal/inferior parietal | R | 32 | –46 | 48 | 439 | 5.11 | 4.59 |
| Temporal | | | | | | | | |
| | Inferior–temporal/medial–temporal | L | –44 | –62 | –6 | 34 | 4.61 | 4.21 |
| Subcortical | | | | | | | | |
| | Thalamus | R | 16 | –10 | –2 | 24 | 4.27 | 3.94 |
| | Thalamus | L | –8 | –24 | 0 | 16 | 3.83 | 3.59 |
| <i>Novel > Skilled, Image</i> | | | | | | | | |
| Frontal | | | | | | | | |
| | Precentral/superior–medial–frontal | L | –22 | 0 | 56 | 144 | 5.20 | 4.65 |
| | SMA | L | –4 | 8 | 52 | 92 | 4.33 | 3.99 |
| | Precentral/superior and medial frontal | R | 26 | –8 | 54 | 137 | 5.05 | 4.54 |
| | Insula/inferior–frontal | R | 38 | 14 | 4 | 18 | 3.72 | 3.49 |
| Parietal | | | | | | | | |
| | Inferior parietal/post-central gyrus | L | –34 | –48 | 44 | 619 | 5.52 | 4.88 |
| | Inferior parietal | R | 40 | –40 | 44 | 145 | 4.06 | 3.77 |
| Temporal | | | | | | | | |
| | Rolandic/Superior–temporal | R | 54 | –24 | 18 | 30 | 4.78 | 4.34 |
| | Hippocampus | R | 22 | –36 | 4 | 24 | 3.86 | 3.61 |
| <i>Skilled > Novel, Move</i> | | | | | | | | |
| None | | | | | | | | |
| <i>Skilled > Novel, Image</i> | | | | | | | | |
| None | | | | | | | | |

in a novel motor sequence (Lotze et al., 1999; Lacourse et al., 2004; Porro et al., 1996) extend to a skilled sequence. It was predicted that execution and imagery-related activations would be more similar in the skilled versus the novel phase, as practice-related remodeling of sensorimotor networks strengthens the spatially distributed motor sequence representation that mediates movement planning and execution (van Mier, 2000a,b). The fMRI data confirm that congruent brain activations are associated with execution and motor imagery in both the novel and skilled phases and that activation features within VOI are more similar in the skilled versus the novel phase.

Activation in the novel phase was greater during execution than imagery in bilateral primary and secondary cortical motor volumes as well as cerebellum. Activation features became increasingly similar for execution and imagery in the skilled phase, however, in a direct statistical contrast, a greater number of voxels were significantly different between execution and imagery in the skilled versus the novel phase. Together, the findings point to neuronal dynamics associated with physical practice that lead to an increasingly congruent functional anatomy to mediate both

execution and motor imagery, while unique sub-processes are engaged to modulate between imagery and movement. In the skilled phase, motor imagery more heavily involves frontal premotor areas, inferior parietal lobe, and medial temporal lobe extending into the supramarginal and angular gyri, while physical execution more heavily involves the precentral/postcentral gyri, superior temporal lobe extending into the rolandic operculum, and the cerebellum.

In a secondary analysis, activation dynamics from novice to skilled learning varied for execution and imagery. For execution, the transition from novel to skilled performance was characterized by a decrease in the extent of activations in primary and secondary cortical motor areas, including a near dropout of activation ipsilateral to the moving hand. For motor imagery, the transition from novel to skilled performance was accompanied by an increase in the extent of frontal and parietal activations.

Motor skill acquisition

The behavioral objective was to execute a self-paced motor sequence task at a rate of 4 Hz. None of the participants achieved

the objective during the NOVEL phase, however, the mean execution rate in the SKILLED phase increased significantly and approached the objective. In contrast to the gain in execution speed, there was no change in the number of execution errors. Increased execution speed is generally associated with a decrease in accuracy (i.e., increased execution errors) according to Fitts's Law (Fitts, 1954), so the gain in speed without an associated gain in errors violates the expected speed/accuracy relationship and indicates a new capability of the motor system to perform the complex motor sequence task (Hallett et al., 1996). The behavioral data clearly establish that a skilled learning phase was achieved following the week of intensive physical practice.

Brain activations in the NOVEL learning phase

The pre-test measured brain activations associated with the performance of a novel motor sequence. Consistent with numerous studies, execution of the novel sequence activated bilateral primary and secondary motor and somatosensory regions extensively, including M1, SMA, PMv, S1, SPL, and cingulate gyrus as well as subcortical structures including thalamus, cerebellum, and striatum (see (van Mier, 2000a,b) for a review). There are similar reports of extensive activations in a novel condition that diminish with practice (Mattay et al., 1998; Tinazzi and Zanette, 1998), suggesting that novel task performance is associated with an unrefined motor control strategy requiring intense executive control (Floyer-Lea and Matthews, 2004), increased attention (Rushworth et al., 2001), or both. It is noteworthy that the sample size used in this experiment was relatively large, providing greater statistical power than is typically available, and may have exposed areas of activation that have not previously been reported in lower-powered studies.

Motor and somatosensory regions previously reported to be active during motor imagery of novel sequences include bilateral M1, SMA, PMv, S1, and cerebellum (Lotze et al., 1999; Porro et al., 1996), though the extent and magnitude of activation are attenuated relative to execution. Consistent with these prior studies, motor imagery of a novel sequence in the current experiment activated motor and somatosensory areas, including M1 (bilateral), SMA (bilateral), PMv (bilateral), S1 (contralateral), IPL (bilateral), striatum (bilateral), thalamus (bilateral), cingulate (bilateral), and cerebellum (bilateral), with local maxima at approximately the same MNI coordinates as for execution, providing further evidence that movement and motor imagery involve congruent motor control processes (Jeannerod, 1994). As in previous studies, activation of motor and somatosensory regions was greatly attenuated during imagery relative to execution.

There are several factors that might explain attenuated motor activation during imagery relative to execution. First, in the present experiment, greater striatal activation was observed during imagery than execution, suggesting the possibility that inhibitory mechanisms may have been engaged during imagery that reduced frontal motor activation. Specifically, striatal activity was weak during physical execution, which is consistent with other studies (see (van Mier, 2000a,b) for a review), but extensive during imagery, possibly pointing to an inhibitory bias on motor processing via striatal–thalamo–cortical circuits (DeLong, 2000). Imagery-associated striatal activation during a novel task has already been reported (Berthoz, 1996; Boecker et al., 2002; Hanakawa et al., 2003), while lesions of the putamen impair motor imagery performance (Li, 2000). We propose that greater striatal activation during imagery compared to execution points to the possible role

of the striatum in an inhibitory network that activates in parallel with excitatory processes during motor performance; the balance of which may determine whether the movement is performed overtly or covertly. This explanation has been proposed for imagined saccade execution as well (Berthoz, 1996).

A second explanation for attenuated activation is the absence of on-line feedback during motor imagery, such that sensory monitoring processes are inactive. Processing of on-line feedback involves mechanisms mediated by parietal and prefrontal areas (Grafton et al., 1992, 1996) that were largely silent during motor imagery. This interpretation is consistent with theories that posit motor imagery as a purely top–down or outflow process (Decety and Ingvar, 1990; Mulder et al., 2003; Paivio, 1986) and not as a bottom–up process as purported by the Psychoneuromuscular Theory (Jacobson, 1931).

The blocked design used to measure the BOLD response in this experiment did not differentiate motor planning from execution processes, so it is unclear whether attenuated activation reflects differences in planning or execution mechanisms or both. Future comparative studies of motor imagery and physical execution should attempt to partition variability in activation due to planning and execution processes (Johnson et al., 2002).

Brain activations in the SKILLED learning phase

The primary question was whether brain activations associated with execution and imagery in a novel learning phase are more or less congruent in a skilled phase. Activation similarity was assessed using a direct statistical contrast of image maps associated with execution and imagery in each phase and by comparing the number of activated voxels within VOI during execution and imagery. The proportion of activated cluster voxels within the VOI during imagery versus execution increased from the novel (36%) to the skilled phase (61%), providing one source of evidence that activation within the VOI became more similar in the skilled phase.

The increase in proportion reflects two major trends in the data. The first trend was a widespread decrease in execution-related activations from novel to skilled phases, including a near dropout of activation ipsilateral to the movement that has been reported elsewhere (Floyer-Lea and Matthews, 2004; Jancke et al., 2000; Lacourse et al., 2004) that may reflect habituation (Eliassen et al., 2001; Loubinoux et al., 2001), a shift from controlled to automatic processing (Jansma et al., 2001), selective inhibition of non-essential muscle activity (Basmajian, 1977), or all three.

It is also possible that attenuated activation of the execution-related fMRI signal is dependent on muscle activity levels (Dai et al., 2001) and those levels may have decreased as movements became more efficient following practice; either fewer muscles were required to execute the motor sequence or less force was required. The dual finding in the current experiment that activation extent decreased and signal magnitude increased in the contralateral precentral gyrus does indeed suggest a refinement of cortical–spinal motor output that would be expected in skilled performance. Electromyographic data were not acquired inside the scanner to verify gains/losses in muscle activation associated with sequence execution, however, it seems less likely that decreased brain activation is only the result of diminished muscle activity because execution rate increased nearly 60% from the novel to the skilled phases, which should have increased brain activation, as signal strength increases with execution rate (Riecker et al., 2003). A secondary task using a constant movement rate might have proved

useful for separating rate- and practice-dependent effects on activation, however, even when rate is constrained before and after practice (e.g., at 2 Hz), activation extent generally decreases in all motor structures (Lacourse et al., 2004). While it cannot be discounted that decreased activations can be explained by increased muscle activation efficiency alone, it seems less likely. Instead, decreased activations associated with increased rate in the skilled phase suggest that the changes were more likely due to learning-related processes such as consolidation (Shadmehr and Holcomb, 1997).

The second major trend in the data was a widespread increase in frontal and parietal cortex activations associated with imagery. In the only other study of imagery-related activations in a skilled phase, Lafleur et al. (2002) reported an overall decrease in activation magnitude within sensorimotor areas, however, the number of activated voxels (i.e., extent) was not reported, and the sample size was comparatively small. Consequently, this is the first report that frontal motor and parietal area activations associated with motor imagery increase in a skilled learning phase.

The greatest shift in activation from novel to skilled phases was in the parietal lobe, where a learning phase \times task interaction of IPL and SPL activation was observed. For both parietal regions, activations were less extensive for imagery than execution in the novel condition and more extensive than execution in the skilled condition. The IPL is typically active during finger sequence learning (Doyon et al., 2002; Grafton et al., 1995; Hazeltine et al., 1997; Honda et al., 1998; Jenkins et al., 1994; Jueptner et al., 1997a,b; Toni and Passingham, 1999; Toni et al., 1998; Sakai et al., 1998) and may play a role in sensorimotor mapping of temporal and spatial relations (Ramnani and Passingham, 2001). Neuronal tracts from the SPL project to the PMv in a parieto-premotor network that transforms somatosensory representations of the environment to muscle-control signals (Krakauer and Ghez, 2000). SPL activation is also found in high attention-demanding tasks (Rushworth et al., 2003).

In the novel condition, sequence execution might have required greater attention resources to process on-line somatosensory feedback than imagery trials, while in the skilled phase, execution becomes automatic, reducing attention resources (Floyer-Lea and Matthews, 2004). In contrast, increased imagery-related activation subsequent to practice might signal a shift in reliance towards internal motor control cues. Specifically, both the SPL and IPL are activated during the planning and execution stages of episodic motor imagery, pointing to a fronto-parietal circuit that participates in the mediation of episodic motor imagery (Hanakawa et al., 2003; Johnson et al., 2002; Sakai et al., 2002; Seitz et al., 1997).

A potential confound is that imagery effort may have increased in the skilled phase while attempting to perform a higher rate of mental finger pressing. Studies have shown a temporal congruence between physical and imagined execution rates (Malouin et al.), so it is predicted that the imagery rate was similar to the execution rate during both the pre- and post-tests.

An intriguing possibility is that episodic motor imagery activates networks that would normally mediate novel movement conditions. Accumulating data point to a two-stage motor learning process, where the first stage is primarily cognitive and characterized by greater attention demands and widely distributed cortical activation, including prefrontal, bilateral sensorimotor, and parietal cortices (Floyer-Lea and Matthews, 2004; Ungerleider et al., 2002). As a task becomes increasingly automatic in the second stage, activation of these regions decreases and subcortical activations increase, including the cerebellum, thalamus, and

putamen. Our finding that imagery-related activations of the frontal and parietal cortices increased in the skilled phase suggests that imagery performance may be reliant on those same executive control elements of motor processing that characterize the controlled processing stage (Lacourse et al., 2004).

A possible confound of multi-session learning experiments is the reproducibility of the fMRI signal (McGonigle et al., 2000; Petersson et al., 1999), such that nonspecific within-session effects may confound learning-related effects. We attempted to control for nonspecific effects by using an interaction design for the fMRI scanning (Petersson et al., 1999), where the activation states (i.e., execution and imagery) were contrasted with a temporally proximate reference state (i.e., rest). The contrast we used ((novel move–reference1)–(skilled move–reference2)) implicitly controlled for nonspecific within-session effects in both the novel and skilled conditions. Combined with a conservative voxel-wise image threshold ($P < 0.05$; whole brain corrected), the observed effects are more likely attributable to learning.

Change in execution-related activations from novice to skilled learning phases

Beyond the contrast of activations associated with execution and imagery within the novel and skilled phases, a secondary question was how activations changed across novel and skilled phases. Previous reports of motor plasticity following physical practice are equivocal, with a balance of studies reporting increased and decreased activations in congruent motor regions that are highly dependent on experimental conditions (van Mier, 2000a,b). The most recent data suggest that performance of a novel motor sequence is mediated by a network that includes frontal cortices, striatum, cerebellum, and parietal cortex (Doyon and Ungerleider, 2002; Floyer-Lea and Matthews, 2004), while performance of a skilled sequence (i.e., automatic) is mediated by a striatal–cortical circuit that includes motor cortical regions (SMA and M1), cerebellar dentate, thalamus, and putamen (Floyer-Lea and Matthews, 2004). The change from novel to skilled performance phases also features a reduction of prefrontal cortex and cerebellar activation.

In the current experiment, the magnitude and extent of execution-related activations decreased in frontal and parietal VOI, increased slightly in ipsilateral cerebellum and vermis, and increased sharply in the striatum. A statistical contrast confirmed that the greatest decreases in activation were in the frontal VOI followed by inferior parietal/supramarginal gyrus, inferior and medial temporal, and thalamus. There were no regions where activation was greater in the skilled versus the novel phase.

The dynamic interaction of cerebellar and striatal circuits is of special interest in motor skill learning, as the striatum may be critical for the storage of well-learned movements (Doyon and Ungerleider, 2002). In this experiment, cerebellar activations were unchanged from the novel to skilled learning phases, a finding that contrasts with reports of increased cerebellar activity with practice (Seitz et al., 1994) and reports of decreased activity with practice (Toni et al., 1998). In the novel phase, only a small number of putamen voxels were activated, and there was no significant activation of the caudate nucleus. In sharp contrast, the caudate was activated in a small number of voxels, and putamen activity increased nearly a hundredfold in the skilled phase. This pattern of plasticity is concordant with findings that early motor skill learning is associated with activation of cerebellar mechanisms, while the basal ganglia increasingly mediate movements as they become

increasingly automatic (Floyer-Lea and Matthews, 2004; Penhune and Doyon, 2002).

Change in imagery-related activations from novice to skilled learning phases

Two large-scale changes in imagery-related activations accompanied motor learning. First, consistent with execution, the transition from novel to skilled learning was accompanied by decreased imagery-related cerebellar activation and increased striatal activation, reflecting a possible shift from cortical–cerebellar to cortical–striatal circuits mediating motor imagery of a skilled movement. Lafleur et al. (2002) similarly reported increased imagery-related activity in the striatum following physical practice of a foot movement that was parallel to execution-related increases. The shift from cortical–cerebellar to cortical–striatal circuits associated with motor learning (Penhune and Doyon, 2002) may be feature of episodic motor imagery as well as execution, extending the notion of functional equivalence of motor representations (Jeannerod, 1994) from novel to skilled performance conditions.

In contrast to execution, the second transition from novel to skilled learning was an increase in imagery-related parietal and frontal activations. Activation of a parieto-frontal network has been shown with motor imagery and may reflect involvement of an action-specific motor representation (Johnson et al., 2002) or increased motor attention (Rushworth et al., 2001). Alternately, because the fMRI BOLD response reflects both inhibitory and excitatory influences (Attwell and Iadecola, 2002), image maps alone cannot reveal whether learning-related changes in activation reflect inhibitory or excitatory influences, making it difficult to interpret activation dynamics. Structural equation modeling (SEM) was used recently to directly compare the effective connectivity among areas activated during movement execution and motor imagery (Solodkin et al., 2004), supplying fresh information about the relative influences of excitatory and inhibitory processes during execution and imagery. In this study, M1 was activated during both execution and imagery, leaving an impression that M1 is activated similarly during these task conditions. SEM revealed, however, that inputs to M1 were different during the two task conditions. Specifically, motor imagery was associated with a notable increase in the influence of the SMA and SPL and intra-parietal sulcus and a decrease in the influence of the PMcV that was interpreted as a suppressive effect. By contrast, these areas had only a weak connection with M1 during movement execution. The increased fronto-parietal activations during skilled motor imagery in this experiment is consistent with Solodkin et al. (2004) and may indicate that a movement suppression mechanism may become incorporated within imagery-related networks in a skilled learning phase.

Implications for motor skill acquisition/re-acquisition and neurorehabilitation

The question of whether a congruent neural substrate mediates execution and motor imagery in both novel and skilled learning phases is essential for neurorehabilitation science because it addresses the efficacy of motor imagery-based mental practice techniques for the retention of skilled movements and the acquisition of new compensatory movements during recovery. This experiment demonstrated congruent activation of motor and somatosensory regions during both novel and skilled learning

phases, supplying neurobiological evidence that motor imagery-based mental practice techniques might be efficacious for the acquisition of new skills and the retention/reacquisition of skilled movements, such as would be needed during neurorehabilitation when movement is disrupted. For example, some evidence suggests that motor cortex activation ipsilateral to movement may compensate for dysfunctional contralateral motor cortex during stroke recovery (Cramer, 2004; Cramer et al., 1997; Strens et al., 2003) and motor imagery activates ipsilateral M1 in a novel condition (Porro et al., 2000). The present findings show that ipsilateral M1 is activated during imagery of a skilled movement as well. There is also evidence that the PMv may have a role in recovery (Frost et al., 2003; Fridman et al., 2004; Johansen-Berg et al., 2002; Seitz et al., 1999) and motor imagery activated the PMv in both novel and skilled conditions. The findings suggest that motor imagery-based mental practice would be efficacious for inducing plasticity of ipsilateral M1 and/or PMv and for skill reacquisition.

Summary

This study was designed to map the functional neuroanatomy of movement execution and motor imagery in novel and skilled learning phases. Image maps were found to be congruent in both novel and skilled learning phases, though variation exists in features of activation and relative involvement of cerebellar–cortical and striatal–cortical circuits. In combination with the findings of Lafleur et al. (2002), the principle of functional equivalence (Jeannerod, 1994) appears to extend from novel learning to skilled learning phases for both upper and lower limb movements. Nearly all features of activation point to greater commonality between execution and motor imagery in the skilled relative to the novel learning phases. From a neurobiological perspective, it is predicted that motor imagery would be efficacious both for rehearsing a skilled movement and for learning a novel movement.

Acknowledgments

The research reported here was supported by the Department of Veterans Affairs, Veterans Health Administration, Rehabilitation Research and Development Service to Dr. Michael Lacourse, Chief, Neuromotor Rehabilitation Research Laboratory, Long Beach VA Healthcare System. We wish to acknowledge and thank Jennifer Altman, Richard Cohen, Lindsey Lastra and Kathleen Turnbaugh for their assistance in recruiting participants and collecting and analyzing data. We wish to especially thank Drs. Jessica Turner, Orhan Nalcioğlu, Tugan Muftuler, and George Chou for assistance in developing the pulse sequences and data collection protocols and for assistance in operating the MR scanner.

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